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A Rare Second Year — Lake Ice Cover in the Canadian High Arctic

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ABSTRACT. Colour Lake, Axel Heiberg Island, N.W.T. (79°25′N; 90°45′W), remained largely ice covered from autumn 1985 to summer 1987. This is a relatively rare event. Observations and measurements of the thickness and specific conductance of the lake ice cover were made at the end of the 1986 summer and again in the following spring. The residual ice cover (second-year ice with first-year ice beneath it) was significantly thicker and had a lower specific conductance than first-year ice formed in marginal leads (moat) that had been ice free in 1986. The first-year ice that grew beneath the residual ice cover had the lowest specific conductance. Distribution of snow on the lake was affected by the roughness of the second-year ice (as compared to the smoother moat ice) and differences in elevation between second-year (high) and moat ice.

Key words: High Arctic, specific conductance, residual ice cover, snow distribution

RÉSUMÉ. Colour Lake, dans l'île Axel Heiberg (Territoires du Nord-Ouest — 79°25′ de latitude Nord, 90°45′ de longitude Ouest) est resteé en grande partie couvert de glace de l'automne 1985 à l'été 1987, ce qui est un événement assez rare. À la fin de l'été 1986 et de nouveau au printemps suivant, on a observé et mesuré l'épaisseur et la conductivité spécifique de la glace qui recouvrait le lac. La couverture de glace résiduelle (glace de deuxième année avec glace de première année au-dessous) était beaucoup plus épaisse et avait une conductivité spécifique plus basse que la glace de première année qui s'était formée dans les chenaux marginaux libres de glace en 1986. C'est la glace de première année, formée au-dessous de la couverture de glace résiduelle, qui avait la conductivité spécifique la plus basse. La répartition de neige sur le lac était influencée par l'inégalité de la surface de la glace de deuxième année (comparée à la glace plus lisse des chenaux) et par les différences de niveau entre la glace de deuxième année (niveau plus élevé) et celle des chenaux.

Mots clés: Extrême-Arctique, conductivité spécifique, couverture de glace résiduelle, répartition de la neige

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INTRODUCTION

Much attention has been given to the character of multi-year sea ice but little to residual (multi-year) lake ice, although reports of polar lakes retaining an ice cover through a summer can be found in the literature (e.g., McLaren, 1964; Coakley and Rust, 1968; Welch *et al.*, 1987). Schindler *et al.* (1974) note that the second-year part of the ice cover on Char Lake, Cornwallis Island (74°42′N; 94°50′W), was thicker at peak ice than the single-year refrozen area around the lake margins. McKay *et al.* (1985) compare ice thicknesses of several perennially frozen Antarctic lakes and present an energy budget to account for them. This note is based on observations of the thickness and type of ice, including snow, on Colour Lake, Northwest Territories, following the 1986-87 winter. By chance, the authors were able to observe the lake during fall 1986 freeze-up. Observations made then and spring ice-cover data from previous years provided a basis for an explanatory description of and some informed speculation about the second-year cover. It is clear that any such cover includes "new" (first summer) and "old" (second summer) ice. In this case, "new" ice grew around and below ice that was present at freeze-up in 1986. We refer to the ice that persisted through the summer of 1986 as "residual" ice.

Readers should be aware that the persistence of lake ice into a second summer is not common at low elevations in the Canadian High Arctic. This is possibly why this is only the second occurrence of this type in more than 25 years of records for this lake.

SETTING

Colour Lake, Axel Heiberg Island, N.W.T. (79°25′N; 90°45′W), is a small (10.2 ha), relatively deep (Zmax = 24.1 m; Z mean = 10.1 m), naturally acidic (winter, under ice, pH of 3.7), hard-water lake in a sedimentary basin (Fig. 1). A more detailed account of the lake, its chemistry and surrounding area can be found in Allan *et al.* (1987).

There is no year-round weather record for Colour Lake, but a variety of data is available for summer months since 1959. The summer weather is comparable to that of Eureka, Ellesmere Island (79°59′N; 85°56′W), located 113 km from Colour Lake (see Blatter, 1985). Eureka has a mean annual temperature of −19.7°C and an average annual snowfall of 44.1 cm (Environment Canada, 1984). Table 1 provides a summary of the 1986 summer mean monthly temperatures and bright sunshine receipts at Eureka, indicating below normal values for both. It has been suggested (e.g., Schindler *et al.*, 1974) that cloudiness, including the timing of cloudy periods, may be a key factor in the break-up of ice on High Arctic lakes.

Although the normal summer at Colour Lake is by no means warm, it is clear from the sporadic records since 1959 (e.g., Caflisch, 1970; Energy Mines and Resources, 1977) that the lake does become ice free most years. Indeed there are only definite records of two years where this was not the case: 1963 (Maag, 1969) and 1986, the summer in which the study of the ice cover discussed below was initiated.

METHODS

We had mapped the ice cover of the lake in previous springs using a grid based on shoreline markers (see Allan *et al.*, 1987). Being in the area for other work, we were able to map, by chaining, the areal extent of "new" and "old" ice after freeze-up in late August 1986 (Fig. 2) and measure thicknesses

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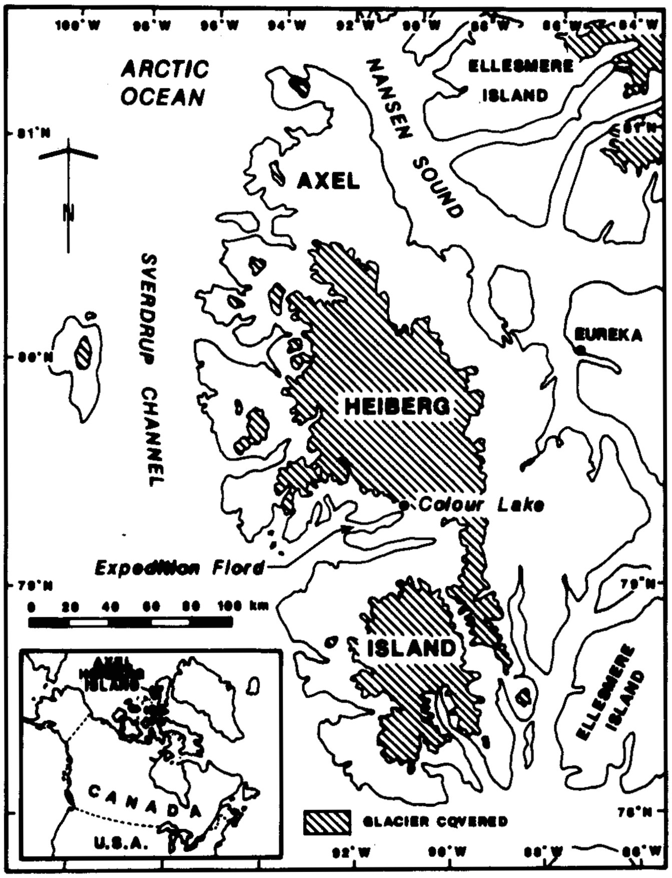

FIG. 1. Location of Axel Heiberg Island and Colour Lake.

TABLE 1. Summary of meteorological data for Eureka, April-August 1986

1986	Mean temperature (°C)	Difference from norm	Bright sunshine (hours)	Normal bright sunshine (%)
April	−26.9	0.7	386.0	108
May	−10.1	0.6	444.0	77
June	− 0.4	−2.2	432.0	106
July	4.3	−1.1	279.0	81
August	2.8	−0.5	159.0	66
September	−11.6	−3.3	93.0	91

Source: Environment Canada, 1986.

along parts of previously used transects. The following May (1987), we remapped the ice cover and took samples for specific conductance measurements to provide an indication of basic chemistry (*c.f.* Wetzel, 1983:183). These surveys provided data that could be compared with those from the August 1986 ice cover and with similar early summer surveys from previous years.

At each survey point, the snow thickness was taken and a hole was drilled through the ice cover. Measurements of type of ice and thickness, along with the hydrostatic water level (the height of the water relative to the ice surface) were recorded. All ice discussed in this paper is "black ice" in the sense that it is crystallographically columnar ice formed by the freezing of lake water. The column-like crystals, "candles," grow downward into the water body. The amount of "white ice," granular ice formed by the slushing of the ice sheet surface, was negligible for present purposes. These methods and terms are described more fully in Adams (1981).

In this paper we refer to residual ice (ice present on the lake at the end of the 1986 melt), sub-residual ice (ice grown beneath the residual ice cover) and residual ice complex, the combination of sub- and residual ice covers. Moat ice is columnar ice initiated in open water around the lake margins at freeze-up in 1986. Examples of residual and moat ice are visible in Figures 3a and 3b.

In fall 1986 we made 15 thickness measurements and in 1987 36 thickness measurements along the transect lines. At the time of the latter survey, one triangular block of ice, approximately 0.5 m × 0.3 m × 0.3 m, was removed from the residual ice cover and another from the moat area (see Fig. 2). Once removed, the ice blocks were sectioned and samples from various levels were rinsed with distilled water, allowed to melt a little, placed in clean plastic bags and allowed to melt completely. Specific conductance was measured using a Barnstead conductivity bridge standardized to 25°C.

RESULTS: THICKNESS

The areal extent of residual ice at freeze-up in 1986 shown in Figure 2 comprised a pan of residual ice covering 63% of the lake surface and smaller floes and loose candles a further 9%. The ice was extensively candled. The main pan was 1.13 m thick over the deepest water, where the pan's centre was located at the time of freeze-up. Ice formed over the remaining 28% of the lake at freeze-up, which occurred on 2 September 1986.

The pattern of ice thickness on Colour Lake the following spring (May 1987) is shown in Figure 4a and the overlying snow cover in Figure 4b. The residual ice areas were evident from their higher surface elevations as compared to the moat ice areas. At freeze-up, the surface of the floating residual ice was ca. 11 cm above the water surface (Figure 5). This difference in elevation affected the distribution of snow on the lake (Fig. 4b). The snow was appreciably deeper over the moat ice zones, with a marked change in depth at the moat/residual boundary.

Snow depths for areas that were "residual" and "moat" in 1987 were not significantly different in 1984 and 1985 (t-test, $P = 0.97$ and 0.70 for each year respectively), but there was significantly more snow ($P = 0.0036$) on moat ice sites in 1987 (Fig. 4b).

Thus, snow was generally thicker around the margins of the lake and thinner toward its centre. This is commonly the case, especially for lakes in higher snowfall locations (e.g., Subarctic), as snow is deflated from exposed centre lake locations to accumulate around the ice-shore boundary (see Adams, 1981). However, as Figure 4b shows, in this case there was, in addition, a peak of snow thickness toward the northeastern corner of the lake, presumably in response to redistribution by up-valley (SW) winds.

The ice thickness survey showed that the residual ice complex (mean: 181.5 cm) was significantly thicker than the moat ice (mean: 162.0 cm) based on a t-test ($P < 0.0005$).

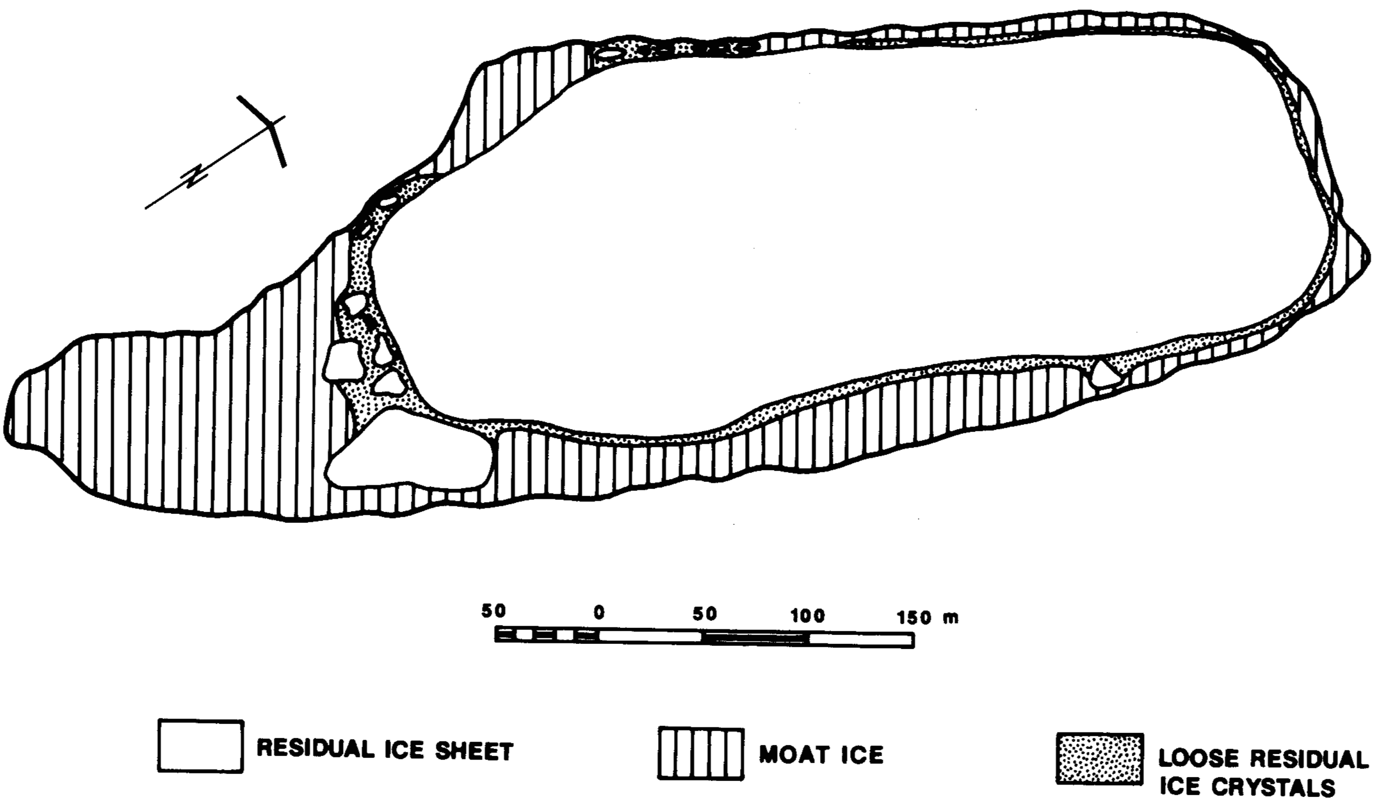

FIG. 2. Distribution of ice at freeze-up, September 1986.

FIG. 3a. Freeze-up September 1986, east side of Colour Lake looking south. Note smooth new moat ice surface and higher, rougher residual ice surface, which initially trapped snow. By the end of the winter, more snow had accumulated in the moat area.

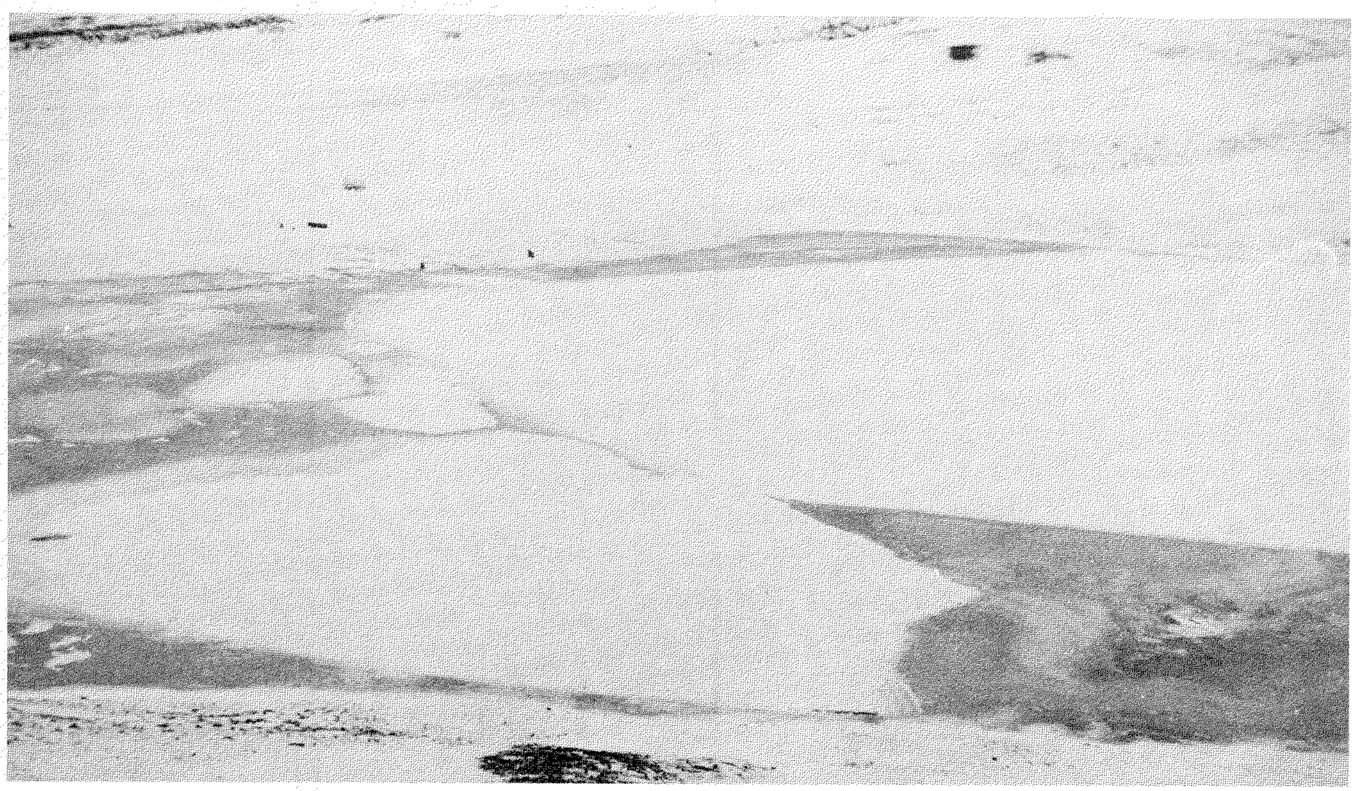

FIG. 3b. A more general overview of Colour Lake, looking west, also in September 1986, to further illustrate points made in Figure 3a. The new, sub-residual ice grew during the winter beneath the pans of residual ice.

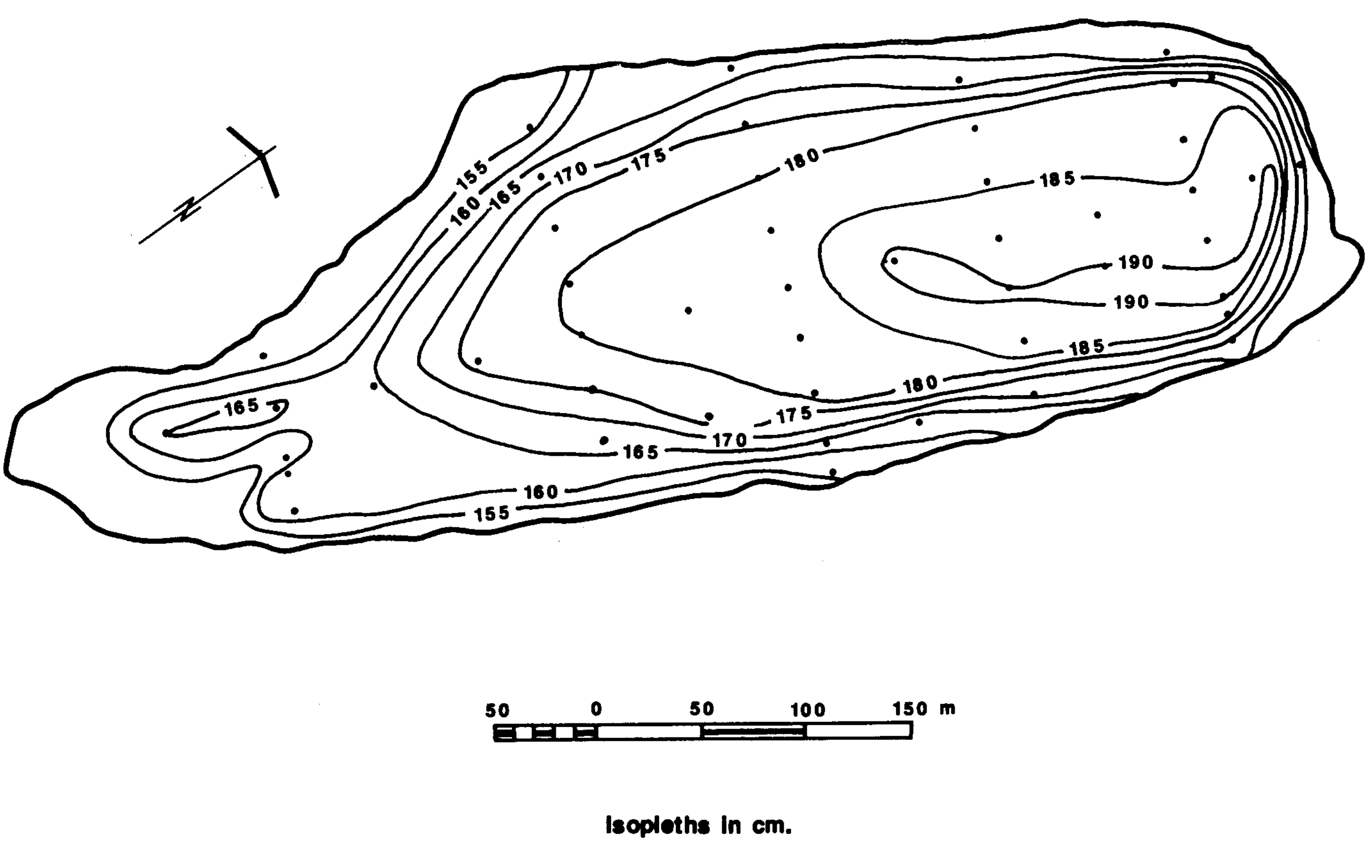

FIG. 4a. Isopleth map of total ice thickness, May 1987.

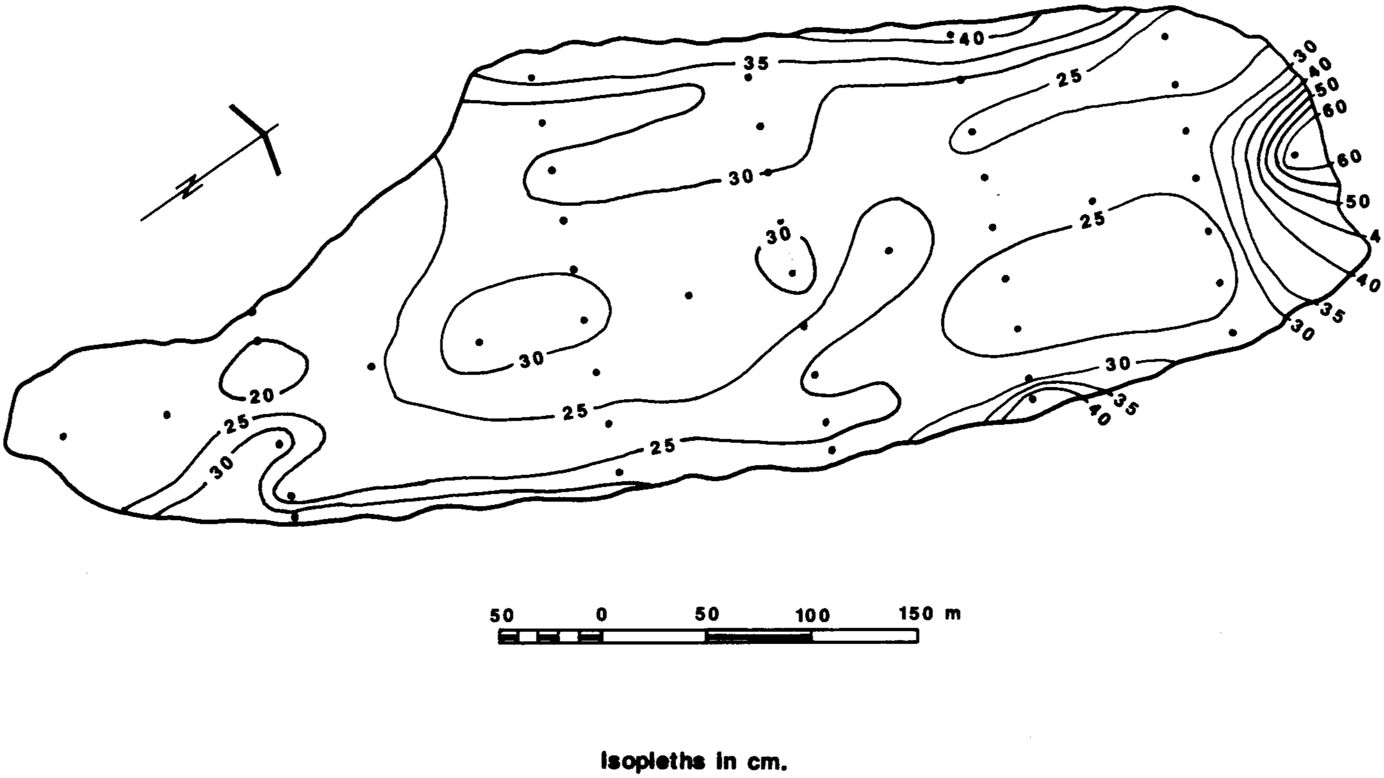

FIG. 4b. Isopleth map of snow thickness, May 1987.

FIG. 5. Residual ice pan on Colour Lake, September 1986. Note the ca. 11 cm difference in elevation between the ice and water surfaces. This persisted after freeze-up. Note also the roughness of the candled ice surface. View is toward northeast.

This same test performed on data from the same areas in previous, "normal," ice years (1984 and 1985, Allan *et al.*, 1987) showed no significant difference (P = 0.25 and 0.86 respectively). The overall pattern was a general increase in the ice thickness from the margins toward the centre of the lake, with greatest thickness toward the northeastern corner (Fig. 4a).

DISCUSSION: THICKNESS

For this effectively current-free lake, with relatively symmetrical bathymetry, it is believed that the normal dominant control of ice thickness is lake snow cover. The importance of snow as the controlling factor has been documented for the High Arctic and elsewhere (e.g., Schindler *et al.*, 1974; Welch *et al.*, 1987). Previous work on Colour Lake also reinforces this view (Allan *et al.*, 1987).

In this particular case, it appears likely that the difference in elevation between residual and moat ice surfaces emphasized the normal margin-to-centre decrease in snow depth. Thick snow on the moat areas insulated the underlying ice, reducing its growth. However, the dominant feature of the end-of-winter ice thickness map (May 1987) was the presence of the residual ice sheet (Fig. 2). Ice growth beneath it was inhibited by more than 1 m of residual ice.

Thus, for the 1986-87 winter, ice was thickest toward the centre of the lake, in part because of the normal relative absence of the insulating and reflecting snow but largely because of the "start" provided by the initial thickness of residual ice (Fig. 5). This point is most clearly illustrated in the northeastern corner, which exhibited *both* thickest snow and ice cover. Prior to freeze-up in 1986, the residual ice sheet was driven into this corner by up-valley winds similar to those that later concentrated snow there.

The nature of the ice and snow cover at peak ice (May 1987) is shown schematically in Figure 6. It will be noted that most "new" ice developed in the moat areas, where by the end of the winter snow was thickest. After freeze-up, the extremely smooth moat ice remained snow free, while the rough residual ice surface retained snow (Fig. 3a). This would have had the effect of further increasing the difference between ice growth rates in the moats and under the residual sheet. However, relatively rapid ice growth in the moats, despite their thick late-winter snow cover, was not sufficient to make up the initial difference of more than 1 m of residual ice elsewhere on the lake.

RESULTS: SPECIFIC CONDUCTANCE

The chemical analysis of the ice blocks reveals a distinct difference in conductance between ice types (Table 2). Using a Mann-Whitney U-test at the 90% level, moat and residual ice conductivities were found to be significantly greater than those of sub-residual ice (P = 0.0184 and 0.0473 respectively). Moat ice conductivity was not significantly different from that of the residual ice (P = 0.6761), although the moat ice had significantly higher conductivities (P = 0.0629) than the residual ice complex as a whole.

DISCUSSION: SPECIFIC CONDUCTANCE

There are several conditions present at the time of formation of the different ice "types" that have an influence on their conductivity.

Specific conductance is an empirical measurement of the concentrations of major ions in ice. This concentration is controlled by the efficiency of exsolution of ions during freezing, which is controlled, in large measure, by the rate of freezing (see Adams and Lasenby, 1985; Shumskii, 1964). Where freezing is rapid, exsolution is inefficient, with the reverse being true when freezing is slow. In the case of columnar lake ice, such as that on Colour Lake, the exsolution takes place into the underlying water column.

For the Colour Lake ice cover, the specific conductances of the moat and the residual ice were similar, both being greater than that of the sub-residual ice. This presumably reflects the efficacy of exsolution in the slower growing sub-residual ice.

Although the residual ice exhibited a lower specific conductance than the moat ice, it was not significantly different. This was somewhat surprising, as we expected that this ice might well have the lowest specific conductance. As an ice sheet melts largely from its surface downward (see, for example, Heron, 1985), the residual ice sheet was presumably composed of crystals from the lower part of the 1985-86 ice cover. These would have been relatively large, pure crystals produced by slow growth below the thickening ice cover late in that winter.

At the end of the 1986 summer, the residual crystals were presumably floating in a layer of low-density, "pure" water produced by the melt of the ice sheet of which they were part. It is not clear how this combination of "pure" crystals and "pure" meltwater would, on freezing, produce an ice sheet with a relatively high conductance. One possibility is that the winds that broke up the cover and drove the residual pan into the northeastern corner of the lake prior to freeze-up produced sufficient turbulence in the lake to bring high conductance water up into the ice sheet between its columnar crystals. The freezing of such water among the crystals would result in concentrations of ions within the ice pan rather than in the underlying water. The high specific conductance of the refrozen meltwater between the crystals might offset the low specific conductance of the crystals themselves.

SUMMARY

Incorporation of residual ice pans into a new ice cover resulted in the residual area being significantly thicker than moat areas at peak ice. The consequent second-year lake ice cover was made up of three distinct ice types, with a conductance hierarchy of: moat ice = residual ice > sub-residual ice. We also noted that the moat ice > the residual ice complex.

There were signs of a "cleansing" of the residual (second-year) ice cover perhaps analogous to that reported for second-year sea ice. This was not as evident as we had expected in the residual ice sheet itself, but the residual ice complex had a significantly lower specific conductance than the single-year moat ice.

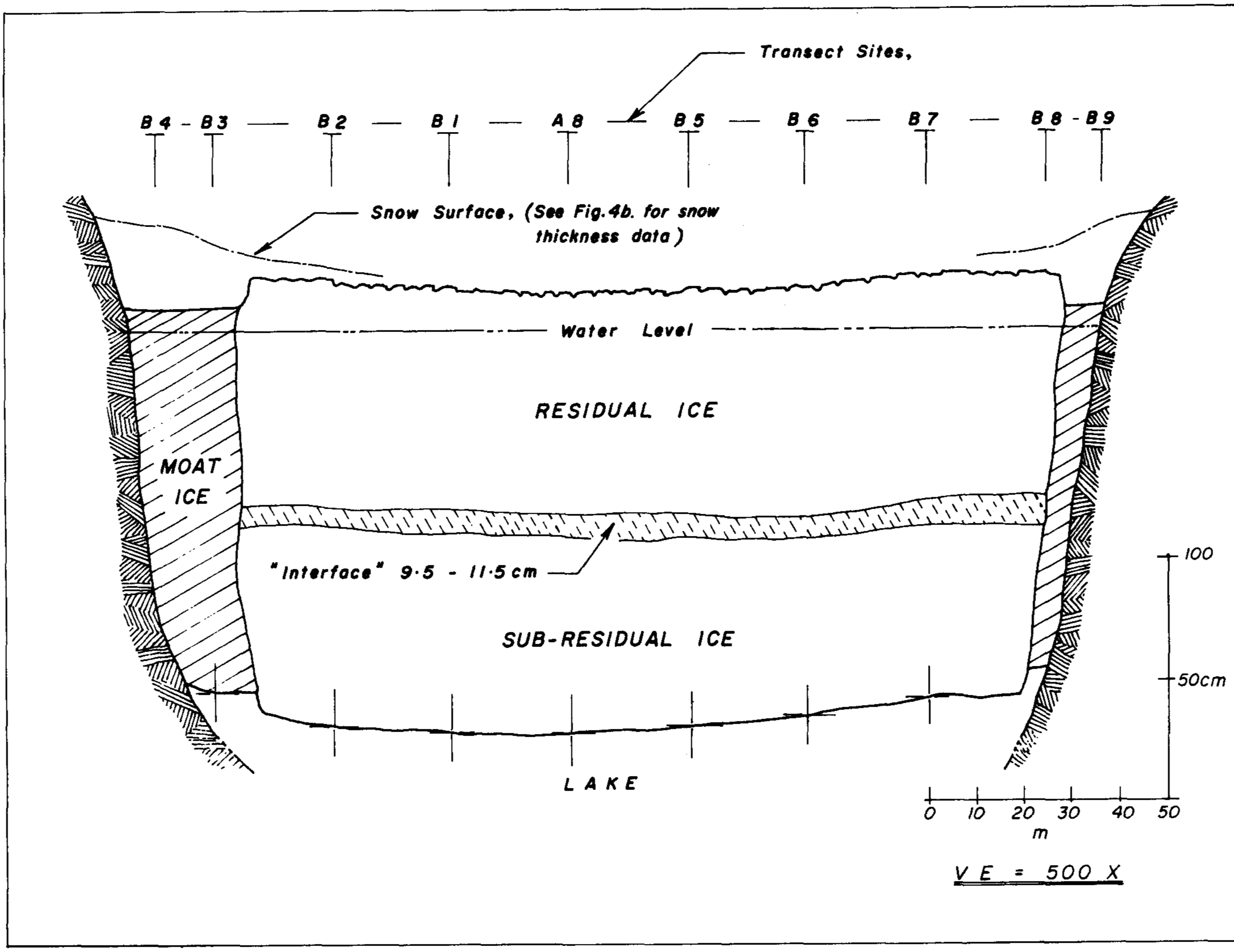

FIG. 6. Schematic cross-section of Colour Lake ice types, May 1987 (vertical exaggeration 500X).

TABLE 2. Specific conductance readings for the 1987 ice cover on Colour Lake

Moat		Residual + ~		Sub-residual + ~	
Depth (cm)	Cond. (uS·cm^{-1})	Depth (cm)	Cond. (uS·cm^{-1})	Depth (cm)	Cond. (uS·cm^{-1})
2.5-23	8.47	0-20	4.68	115-130	2.51
23-68	3.72	20-40	7.76	130-145	3.83
68-90	6.99	40-60	4.44	145-160	3.77
90-100	6.12	60-80	4.76	160-175	2.87
100-150	4.21	80-95	2.75	175-181	3.34
mean =	5.90	mean =	4.88	mean =	3.26
s.d. =	1.97	s.d. =	1.81	s.d. =	0.57

+The interface between residual and sub-residual (95-115 cm) had a conductance of 6.06 uS·cm^{-1}.
~The residual ice complex had a mean conductance of 4.07 uS·cm^{-1} (s.d. = 1.52).

The snow cover distribution on Colour Lake was thicker around the margins and thinner toward its centre. This is a pronounced change from two previously monitored years, where there was no significant variation in snow depths on the lake. We believe that the 1986-87 ice cover, its roughness and topography, influenced the observed 1987 spring snow cover pattern.

ACKNOWLEDGEMENTS

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